

# **Aerocapture Instrumentation Shortfall Assessment**

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## **OBJECTIVE**

This report addresses two tasks as indicated below:

1. Research and identify currently available instrumentation such as pressure, thermal and stress sensors for Aerocapture/ballutes and regression rate measurements for ablatives in aeroshells. Assess available instrumentation capabilities/applicability for Aerocapture requirements.
2. Identify and document current instrumentation materials related shortfalls in order to provide insight into areas where advancement in materials and/or processes might significantly improve utility of the instrument for the Aerocapture mission.

## **APPROACH**

The outline of this report basically follows the objectives noted above and reflects the most relevant information obtainable, based upon the experience of the researchers. Certain baseline information about the structures to be instrumented and their potential environment guided the search for pertinent sensor technologies. Programmatic documents were consulted for proposed ballute configurations – trailing ballutes, afterbody and forebody . Sensor technologies were considered in terms of their operation in the environments of Mars and Titan.

Reference documents are too numerous to list but are on file should specific requests be forthcoming from the Aerocapture community.

To perhaps provide additional insight from the materials perspective, the principle of operation for several important and time proven devices is provided. This may lead a materials science researcher to consider additional efforts or avenues not apparent to the sensor personnel.

## **I. CURRENT SENSOR TECHNOLOGY BASICS**

### **THERMAL**

1. Thermocouples – most commonly used devices for temperature over a range of 10° K to 2583° K. The thermocouple operates on the principle of the Seebeck effect and requires a reference junction which adds to power requirements, size and weight and would tend to make them inappropriate for ballute applications.
2. Resistive Thermal Devices (RTD) – are typically manufactured in one of two ways - platinum wires (wound on mandrel or mounted on substrate) or platinum film (thin film deposited on substrate, ceramic or other material such as Kapton). They have a positive temperature coefficient of resistance which means as temperature goes up the resistance goes up. As the sensor itself decreases in size, this decreases the total resistance and decreases sensitivity. Thin film type RTD's may provide high sensitivity in a small envelop. The current required for an RTD measurement is typically much higher than that for a thermistor, a factor of approximately 5 to 10.
3. Thermistors - typically manufactured by doping a metal oxide. This produces a semi-conductor with negative temperature coefficient. While these devices can be as small as a pin-point, their time response increases with decreased size, the dissipation constant becomes a significant consideration and signal conditioning becomes greater issue. These devices are not considered to be the best approach for thermal measurements on ballutes.

**MEMS** - Micro-electromechanical (MEMS) technology does have applications in the field of thermal sensors, most notably in RTD sensors. One notable configuration utilizes a sensor film (platinum) deposited on silicon nitride membrane. A layer of gold is used to minimize the lead resistance.

Since the goal is to maximize sensitivity in these thermal devices, it is necessary to maximize the operating temperature while minimizing the dissipated power. Thermal losses will be manifested due to conduction through electrical leads to a substrate and conduction through supporting structure to substrate. Trade-offs are made to use low resistivity material in lead wires which usually guarantees high thermal conductivity. Heat conduction to the substrate is typically addressed through design and manufacturing techniques. The choice of materials for these type devices is limited and combinations are constrained by processing technology capabilities. Some materials have excellent mechanical properties, but poor thermal or electrical properties, etc.

**Optical** - Optical technology is also used in various temperature measuring devices. FISO Technologies, Inc. has a temperature sensor that operates on principle of thermal expansion of highly stable glass. This Fabry-Perot measuring device has a temperature range from -40° F up to 572° F, has a fast response, and is small and lightweight.

Another fiber optic technique employs the use of a semi conductor crystal such as GaAs to absorb injected white light. The light that is not absorbed is reflected back down the fiber by a dielectric mirror where it is measured by a spectrometer. The position of the absorption shift is analyzed and correlated back to temperature. (Nortech Fibronic, Inc).

In each of these optical techniques, the fiber-optic temperature probe must be in contact with the material it is measuring.

Other fiber techniques include the use of a luminescing phosphor attached at the end of an optical fiber or a refractory metal that forms a blackbody cavity attached at the end of a sapphire rod.

In general fiber optics are good sensor choices because of immunity to EMI and RFI, however they **cannot be creased** and as protected fibers (encased in claddings and jackets) are even more rigid and bulkier. Additionally, optical rods, predominantly quartz or sapphire, are extremely shear sensitive.

### **PRESSURE**

1. Strain Gage pressure transducers - convert pressure into change in resistance due to strain induced by the movement of an element or diaphragm. The strain-gage element can be unbonded, bonded metal wire or foil or semi-conductor, deposited film, sputtered thin film and other materials.
2. Capacitance - metal diaphragm separates two volumes. Stationary metal plates are positioned on each side of the diaphragm such that deflection of the diaphragm changes the capacitive coupling between the diaphragm and the plates.
3. Differential Transformer - a diaphragm is often used as force summing device and linked to push rod or linkage to displace a magnetic core within a transformer which produces unbalance within two secondary windings.
4. Potentiometric - consists of a resistive element and a movable wiper which is attached to the force summing device.
5. Variable Reluctance - uses the ratio of the reluctance of the magnetic flux path of two coils and requires only a small motion of their force summing device to produce a useable output. Typically 28 V DC input to AC to DC conversion circuitry in providing a 0 to 5 V output signal.

Of these five standard type pressure measuring techniques, two are more applicable to ballutes due to miniaturization techniques - the strain gage and capacitance types.

**MEMS** – Much work has been done in this area for pressure measurements including acoustic sound pressure levels. Numerous capacitance and piezoresistive sensors have been designed and manufactured using various processes including dissolved wafer processes and silicon micromachining/etching. Silicon pressure sensors are in many cases only as good as their packaging – they require protective coating or package. Organic and inorganic die attach materials can be used, however organics may produce outgassing and not be appropriate in high temperature regimes. Coefficient of thermal expansion (CTE) of the die attach material and substrate is extremely important in sensor design since mismatch may induce stress, which contributes to much of the error in commercial piezo-resistive-based sensors.

**Optical** - Current optical techniques are available from FISO Technologies, Inc. which has two sensors operating with a Fabry-Perot interferometer in environments up to 150° C. Aside from dealing with fiber optic cable, thermal environment issues exist in this case due to approximately 500° C temperatures predicted internal to the ballute structure.

MEMS variations of the Fabry-Perot exist by etching the Fabry-Perot cavity which lies between dielectric film stacks and serves as the pressure sensitive element. Multiple dielectric films (usually consisting of silicon dioxide and silicon nitride) can be deposited to form wavelength selective dielectric mirrors.

Present development efforts in the area of MEMS pressure sensing may prove viable candidates for ballute application, but further investigation would be required. Actual in-house testing or thorough evaluation in concert with vendor/developer is recommended.

### **STRESS/STRAIN**

1. Bonded Metallic Wire Gages and Semiconductor Strain Gages - wire strain gages come in many resistances, gage factors and various configurations such as the quarter bridge, half-bridge, rosette, and full bridge. These gages must be bonded to the test item.
2. Thin Film Strain Gage- thin film strain gage eliminates the need for adhesive bonding by first depositing an electrical insulation onto the stressed surface and then depositing the strain gage onto this insulation layer. Work has been done in this area to produce a semiconductor material that can be prepared as a thin film and used as the sensing element. Potentially this technique could be configured/packaged for a pressure and strain measurement.
3. Optical Fiber Strain Gage - many fiber optic strain gages are designed around a Fabry-Perot interferometer(FPI) consisting of two mirrors facing each other deposited on tips of two optical fibers inserted into a microcapillary. Light reflected in the FPI is wavelength-encoded in exact accordance with cavity length. Another way of using fibers is through the application of a Bragg diffraction grating which operates by changing the color of the light field in the fiber(wavelength modulation).

**MEMS** – One novel approach for measuring strain is the use of electrical capacitance whereby the electrically conductive material itself is part of the material used for the structure on which strain is to be measured. Further investigation would be warranted for determining whether the method held promise for ballutes and proper conductive materials could be inserted into a ballute structure. Primarily for surface or seam strain, wired and wireless approaches should be considered.

Overall, MEMS technology in this area for strain is essentially the same technology as for pressure transducers. This leads to the possibility of using one sensor for both internal ballute pressure and surface strain.

**Optical** - While optical fibers are been deemed inappropriate for ballutes, based upon our understanding of mission operations, due to problems with creasing, several comments should be made relative their use as strain monitors. The particular approaches, as listed below, should be considered very low TRL from a sensor perspective and in some cases from a materials perspective: (1) Using notched fibers that produce a phase change when stretched could be monitored by appropriate vehicle mounted instrument. (2) Use of fluorescent techniques with fibers to produce a material that fluoresces when exposed to some light. A materials issue could be determining what would fluoresce. A photodiode might be the pickup. However, as indicated, one would still be dealing with a fiber that cannot be “creased”. Furthermore, would have additional problem of doping fibers to fluoresce and of bonding the fibers to structure.

**Trailing Ballute Specific** - Load cells have strain gages on beams internal to load cell. An example application would be to mount load cell to vehicle with screw or whatever method and run the tether through a load cell eyelet. The state-of-the-art (SOA) in load cells is limited to 250° F so thermal is an issue. Sizes can be as small as <1 inch depending on load to be measured. There are thin films load cells but limitations here are thermal also. A high temperature material with near 0 thermal coefficient of resistance would eliminate any thermal problems and be applicable to thin film pressure measurements also.

### **REGRESSION RATES - Aeroshells**

**ARAD** - The ARAD sensors are comprised of a narrow rod of carbon phenolic wrapped with alternating layers of insulating tape(Kapton), Platinum-Tungsten wire, more insulating tape and Nickel ribbon. The resistance of the Platinum-Tungsten wire is much higher compared to the Nickel. ARAD operation is based on the fact that char produced by the ablating phenolic and Kapton is electrically conductive. An electronic circuit supplies a constant current as excitation. The Platinum-Tungsten wire, char and phenolic loop complete the circuit. The voltage is measured across the Nickel sensing wire and the Platinum-Tungsten wire. As the phenolic ablates and recesses, the Platinum-Tungsten wire is shortened and its resistance decreases.

**Thermo Plug** - A second simple method of measuring recession is embedding thermal sensors in ablating materials at known distances from the surface. As the material ablates the sensor’s output is indicative of the ablation status.

Both of the above regression rate approaches are based upon time proven thermal measuring devices. It is critical, however, that they be thoroughly investigated in proper environments, by qualified instrumentation engineers for operational issues that might be materials related. HyTEx Aerothermal Ground Test Series report, dated June 10, 2005,

indicates tests of the above two techniques, ARAD and Thermo Plug, produced unsatisfactory results for these tests.

**Optical** – Various embedded fiber optical techniques may be able to provide erosion or ablative information. These may operate through a time-of-flight approach or other fiber optic techniques. Consideration must be given to the fiber materials so that they are not ablating faster than the materials they are housed in.

**WIRELESS for all measurements** - Need power at both ends and very small size for both transmitter and receiver. Integrated circuit technology is enabling RF MEMS adaptations and is strong area for research, promising on-chip switches with zero standby power consumption, low switching power and sub-5V actuation voltage; high quality inductors, capacitors and varactors; highly stable oscillators and high performance filters operating in the tens of MHz to several GHz frequency range.

Advances in power management include solar cell (photovoltaic) which many companies use to recharge batteries in wireless sensors. There are ongoing studies to advance power harvesting.

## **II. APPLICABLE SENSOR TECHNOLOGIES**

As previously indicated, all sensor technology was considered for application to ballutes. Contact with MSFC's Solar Sail project office did not yield any pertinent information as to sensor selection for ballutes.

Given the storage condition and operational environment of ballutes, we do not believe optical fiber technology to be a viable option for ballutes. We would rule out all standard pressure measuring techniques except strain gage and capacitance transducers. In the thermal arena, rule out thermocouples due to reference compensation which makes more complex and bulky, and rule out thermistors because of their limited temperature span of less than 100 degrees.

Therefore, from the sensor perspective, RTD's; strain gage and capacitance techniques for pressure; thin film, bonded metallic wire and semiconductor techniques for strain are the best measurement approaches. MEMS research into these techniques exists and some general statements concerning their fabrication need emphasizing.

Several enhancements to MEMS production should be considered, including simplification of the photolithographic masking steps and/or process geometries to enhance throughput, availability, delivery, and cost. The transducers need a higher sensitivity. The etching technique should be improved to provide better diaphragm thickness control.

Fabrication requirements of microelectronics and of optimal sensing are often in conflict (for example, electronics cannot tolerate any high temperature processing steps), and thus

their integration often results in compromised electronics functionality and compromised sensor design.

### **III. RECOMMENDATIONS**

A compilation of the most relevant recommendations are as follows:

- Two of the most significant improvements needed in materials science are developing materials to (1) minimize the thermal coefficient of resistance by design or compensation and (2) reduce the thermal coefficient of expansion of the substrate to match the CTE of the die and the die attached materials to minimize thermal mechanical stresses in the package in high temperature materials.
- Explore silicon carbide and silicon nitride and other materials for RTD's to maximize performance characteristics in higher temperatures.
- ILC Dover has used conductive threads for electrostatic charge dissipation but these fibers/wires with a connector could provide means of measuring pressure, stress, temperature. Flexibility, conductivity as related to materials coatings, change in resistivity due to flex, tensile strength, post abrasion tensile strength would be primarily materials issues.
- Power management is an enabling technology for wireless communication and any materials research along the lines of battery manufacture would be extremely beneficial. Another materials issue includes high temperature material for MEMS components to address RF transmitter/receiver development along with materials that promote "self-powering" sufficient to transmit signals in relevant environments. Typical needed material characteristics might include piezoelectric, ferroelectric, and pyroelectric.
- Initial studies indicate a thin film of materials such as indium-tin-oxide (ITO) might be applied to ballute material for strain measurements. These semiconductor materials yield a considerably larger gage factor than bonded metallic strain gages, but ballute application/adaptation feasibility should be researched.
- Commercial manufacturers build similar type recession gages as the ARAD. For the projected use of any of these devices, whether ARAD or COTS, in a lunar or Mars mission, significant materials compatibility and packaging studies are required.
- All ballute sensor technologies recommended herein will require bonding, so robust adhesives will be critical.